

Precision Measurement of the W Mass and New Physics

1. Why?
2. W Mass: Status and Measurement Techniques
3. Status of Theory Calculations for W/Z Production
4. Conclusions

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1 – Why?

- The LHC is a discovery machine. Why should we measure the W mass, and more generally, do precision physics at such a facility?
- After all a precise measurement of M_W in a hadron collider environment is no walk in the park (see talks by **Ashutosh Kotwal, Junjie Zhu**)
- more bluntly:
“I rather commit suicide than measure M_W at the LHC” (**Guido Altarelli at an early LHCC meeting**)

- Which measurements are of interest?

➤ m_t , M_W and $\sin^2 \theta_W$

→ make it possible to constrain the mass of the SM Higgs boson:
winter 2010: $M_H < 155 \text{ GeV}$ (95% CL)

one-loop corrections to M_W and $\sin^2 \theta_W$ depend logarithmically
on M_H

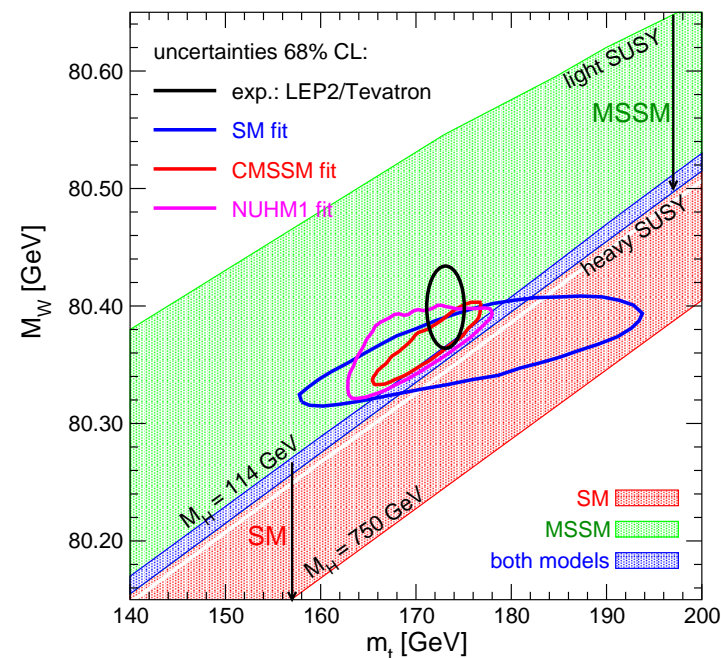
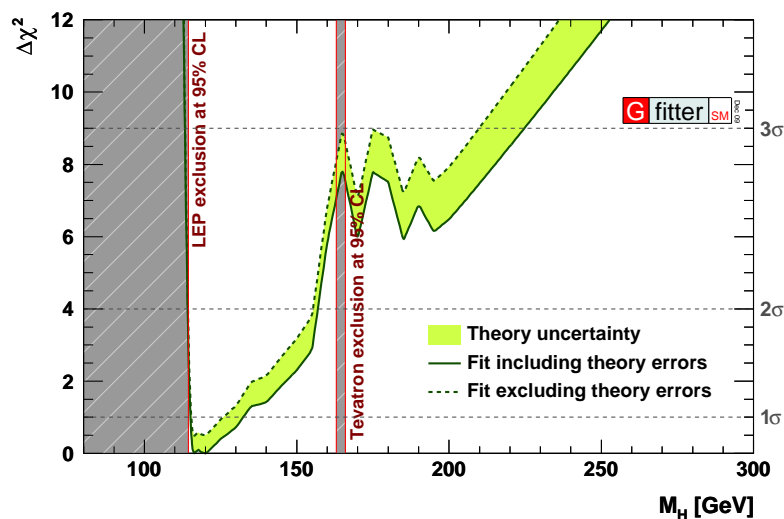
→ thus providing a consistency check on the SM (once a Higgs boson
candidate has been observed)

→ may give hints of new physics, or provide constraints on new physics
models

new particles contribute to the one-loop corrections

Data in better agreement with SUSY models than SM

but this is not surprising as SUSY models have more free parameters



CMSSM: Constrained MSSM

NUHM1: a common SUSY-breaking contribution to the Higgs masses is allowed to be non-universal

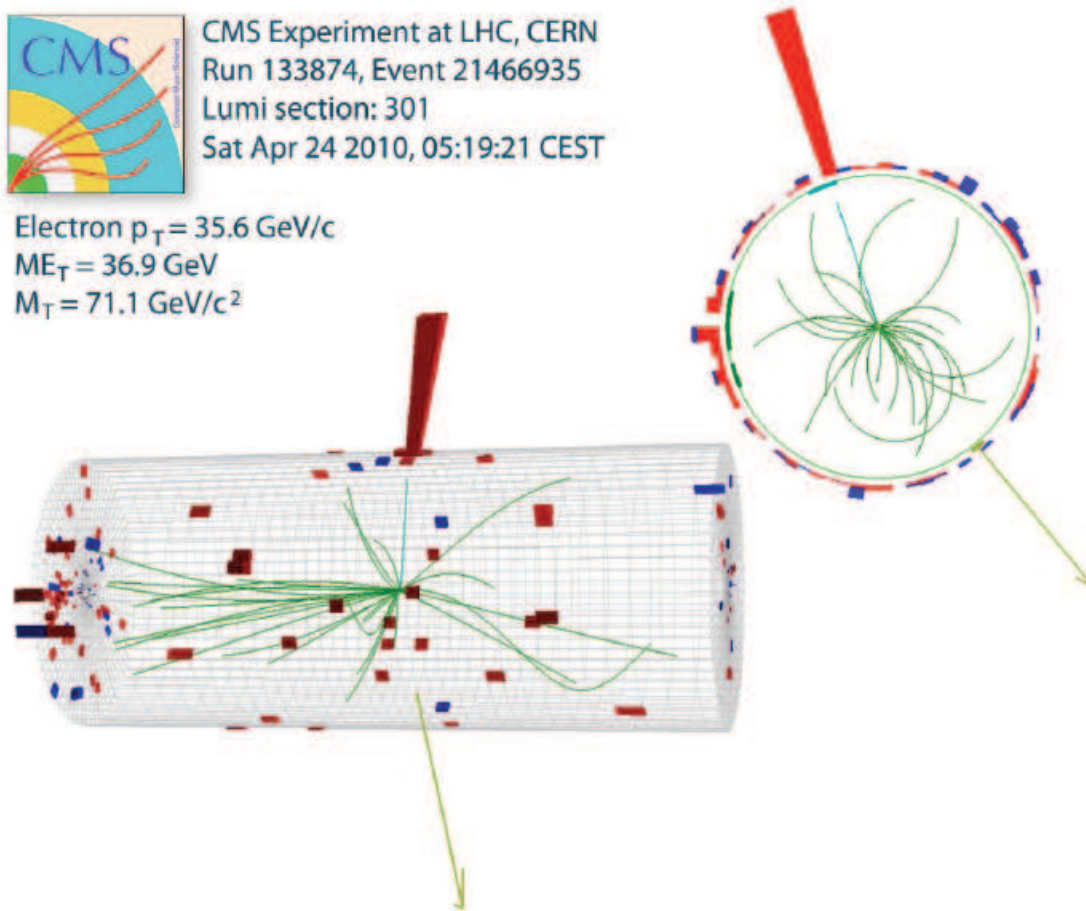
W and Z Production has been observed at the LHC

$W \rightarrow e\nu$ candidate



CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST

Electron $p_T = 35.6$ GeV/c
 $ME_T = 36.9$ GeV
 $M_T = 71.1$ GeV/c²



$Z \rightarrow ee$ candidate

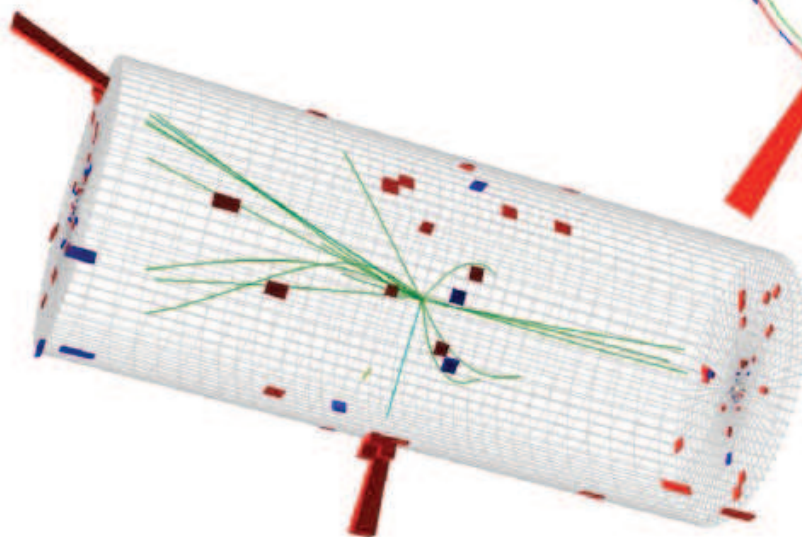


CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

Electrons $p_T = 34.0, 31.9$ GeV/c
Inv. mass = 91.2 GeV/ c^2

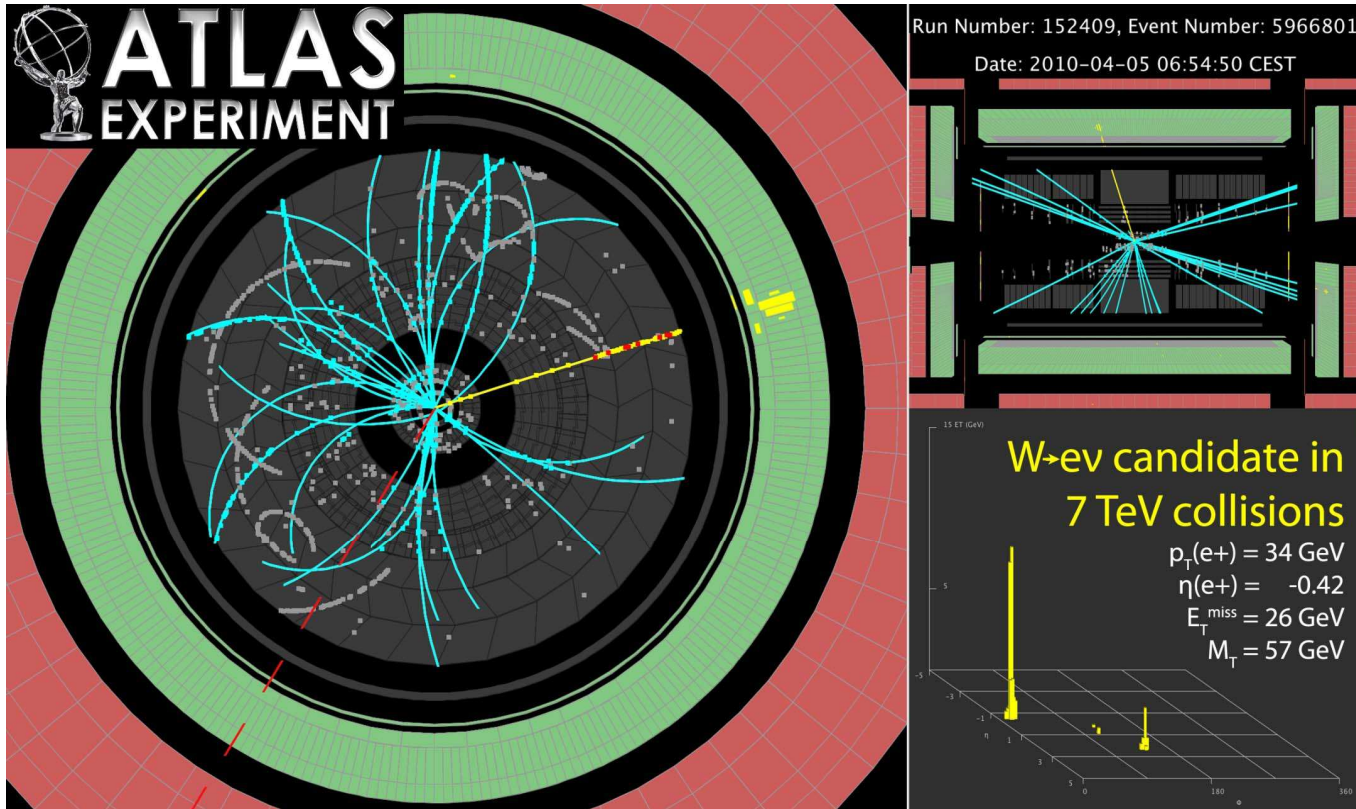


ee mass: 91.2 GeV



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$W \rightarrow e\nu$ Candidate



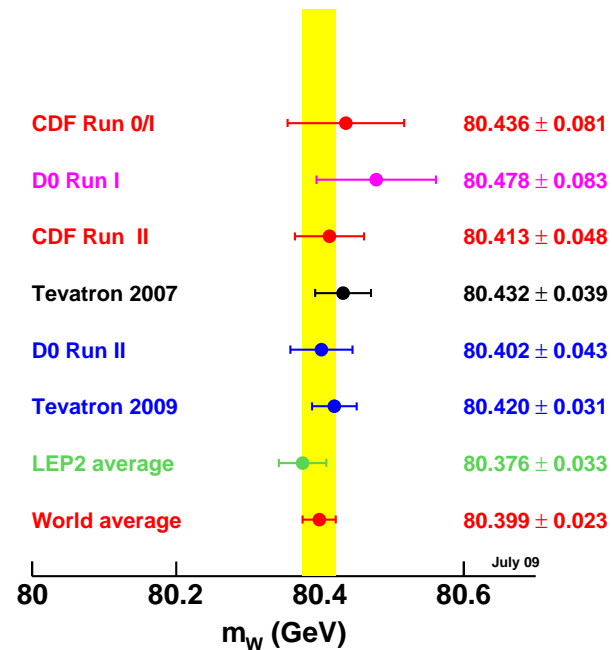
Pheno 2010 Symposium, Madison, Wisconsin, May 10-12, 2010

Jianming Qian (University of Michigan) 17

- expect a torrent of W 's and Z 's at the LHC in the near future
- for $\sqrt{s} = 7$ TeV:
 $\sigma(W^\pm \rightarrow \ell\nu) \approx 10.5$ nb
 $\sigma(Z \rightarrow \ell^+\ell^-) \approx 0.96$ nb
- cross section approximately doubles for $\sqrt{s} = 14$ TeV

2 – W Mass: Status and Measurement Techniques

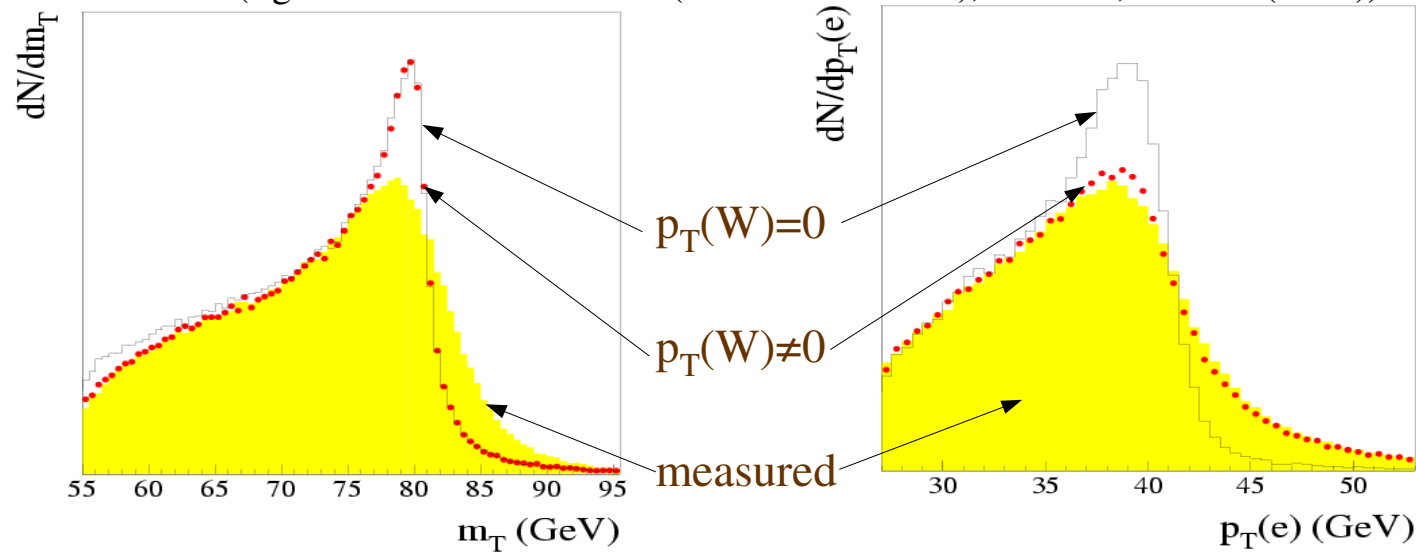
- current W mass results:



world average: $M_W = 80.399 \pm 0.023$ GeV

- CDF measurement based on 0.2 fb^{-1}
- $D\bar{O}$ measurement based on 1 fb^{-1} ; electron channel only
- CDF expectation: $\delta M_W = 25 \text{ MeV}$ for 2.4 fb^{-1}
- techniques used: transverse mass (M_T), and lepton transverse momentum ($p_T(\ell)$) distribution

(figures from Abbott *et. al.* (D0 Collaboration), PRD 58, 092003 (1998))



- $M_T = \sqrt{2p_T(\ell)p_T(\nu)(1 - \cos \phi_{\ell\nu})}$ distribution:
 - ➡ independent of $p_T(W)$ to first order
 - ➡ detector effects dominated by resolution for p_T of neutrino (ie. the missing transverse momentum, \cancel{p}_T)
 - ➡ M_T distribution thus is sensitive to hadronic recoil (and its modeling) and multiple interactions
- $p_T(\ell)$ distribution:
 - ➡ sensitive to $p_T(W)$ (ie. to higher order QCD corrections)
 - ➡ insensitive to \cancel{p}_T resolution

- LHC expectations:

- ☞ ATLAS: $\delta M_W = 7 \text{ MeV}$ for 10 fb^{-1} per lepton channel using the M_T and $p_T(\ell)$ distributions ([arXiv:0805.2093](#))

- need excellent understanding of detector (lepton scale and resolution, p_T resolution) to achieve this

- assumes that PDF uncertainties can be controlled such that they contribute only 1 MeV to δM_W

- assumes that needed theoretical tools will be available to achieve a 1 MeV uncertainty from unknown higher order corrections

- ☞ CMS: $\delta M_W = 40 \text{ MeV}$ (20 MeV) for 1 fb^{-1} (10 fb^{-1}) using the scaled observable method and the so-called morphing method ([J. Phys. G 34 \(2007\), N193](#))

- need

$$\delta M_W \approx 7 \times 10^{-3} \cdot \delta m_{top}$$

for equal contribution to M_H uncertainty from m_{top} and M_W

☞ **Tevatron: $\delta m_t = 1.4 \text{ GeV}$ (and counting down...)**

☞ expect $\delta m_t \approx 1 \text{ GeV}$ at LHC

☞ limited by non-perturbative QCD effects, which introduce theoretical uncertainty $\delta m_t = \mathcal{O}(\Lambda_{QCD})$ (renormalon uncertainty)

→ $\delta M_W < 10 \text{ MeV}$ should be goal for LHC

Food for thought...

- However, there are important differences between the Tevatron and LHC W mass analyses which have been ignored in the CMS and ATLAS estimates (Dydak et. al., arXiv:1004.2597):
 - ➡ Tevatron: $\sigma(W^+) = \sigma(W^-)$ (CP invariance)
 - ➡ LHC: $\sigma(W^+) \neq \sigma(W^-)$
 - ➡ cannot pursue a 'charge-blind' analysis at the LHC:
 - W^+ production: $u\bar{d} + c\bar{s}$
 - W^- production: $d\bar{u} + s\bar{c}$
 - Z production: $u\bar{u} + d\bar{d} + s\bar{s} + c\bar{c} + b\bar{b}$
 - ➡ uncertainty on $u_v(x) - d_v(x)$, $s(x) - c(x)$, and c and b -quark PDF's is what counts
 - ➡ Biases from current uncertainties in the PDF's of 1st (2nd) generation quarks introduce an uncertainty on M_W which may be much larger than the target precision

- Remedies:

- ☞ Need a dedicated charge specific LHC analysis programme (didn't we know that already?)
- ☞ targeted to constrain $u_v(x) - d_v(x)$ and $s(x) - c(x)$ (asymmetry of the ℓ^+ and ℓ^- p_T spectra)
- ☞ run at two center of mass energies $\sqrt{s_1}$ and $\sqrt{s_2} = (M_Z/M_W)\sqrt{s_1}$ (same momentum fractions of quarks that annihilate to W and Z)
- ☞ reduce current of magnet by a factor of M_W/M_Z to equalize curvature radius for leptons from W and Z decays
- ☞ reverse the magnetic field in the detector (detectors are not invariant under parity)
- ☞ need to run with light isoscalar ion beams (deuterium, helium) to reduce the $u_v - d_v$ PDF uncertainty
- ☞ or do a dedicated μN scattering experiment

- can also measure $M_{W^+} - M_{W^-}$ (Fayette *et al.*)
 - ➡ tests CPT invariance
 - ➡ constrains BSM physics
 - ➡ currently: $M_{W^+} - M_{W^-} = 257 \pm 117 \text{ MeV}$ (electron channel) and $M_{W^+} - M_{W^-} = 286 \pm 136 \text{ MeV}$ (muon channel) (CDF)
 - ➡ uncertainties are much larger than for charge averaged measurement: trade off between control of detector to positive and negative particles over full detector and relative control of charge-averaged detector response in left and right sides of detector
 - ➡ can achieve $\delta(M_{W^+} - M_{W^-}) = \mathcal{O}(10 \text{ MeV})$ if strategies are implemented which constrain PDF's to guarantee that $\delta M_W = 10 \text{ MeV}$ can be achieved (see above)

Measuring M_W : The Scaled Observable Method

- Conceptually discussed in Giele, Keller, PRD 57, 4433 (1998)
- basic idea: use known Z boson parameters (mass, width) for calibration and measure M_W using the ratio of scaled transverse mass distributions for W and Z
 - ➡ **advantage**: many uncertainties cancel in ratio
 - ➡ **disadvantage**: precision limited by Z boson statistics ($\sigma(Z \rightarrow \ell^+ \ell^-) \approx 1/10 \times \sigma(W \rightarrow \ell \nu)$)
 - ➡ relies on detailed understanding of the detector response by means of MC simulations compared to control samples

Measuring M_W : The Morphing Method

- basic idea:
 - ➡ scale down M_Z and momenta of Z decay leptons such that $M_Z = M_W$
 - ➡ morph one Z decay lepton into p_T with the correct resolution
- same advantages, disadvantages and theory requirements as for scaled observable method

3 – Status of theory calculations for W/Z production

- the NNLO QCD corrections to W/Z production are known in fully differential form (**Melnikov, Petriello**) and are available in form of a parton level MC program (**FEWZ**)
- resummed NLL QCD corrections (soft gluon resummation) are known (**RESBOS**)
- NLO QCD corrections have been merged with HERWIG in **MC@NLO** and **POWHEG**
- several calculations of the full $\mathcal{O}(\alpha)$ EWK corrections to W/Z production exist (**UB, Wackerroth [WGRAD, ZGRAD]; Bardin *et al.* [SANC]; Carloni Calame *et al.* [HORACE]; Dittmaier, Denner; Jadach *et al.* [WINHAC]**)

- $\mathcal{O}(\alpha)$ electroweak (EWK) corrections to W/Z production

- ☞ 1-loop: naively of $\mathcal{O}(\alpha) \leq 1\%$

- ☞ why bother?

- ☞ EWK corrections may be enhanced by large

- collinear logs: $\log(\hat{s}/m_f^2)$, relevant near the W/Z peak

- Sudakov logs: $\log(\hat{s}/M_{W/Z}^2)$, relevant at large di-lepton masses

- ☞ QCD corrections may be small (example: QCD corrections largely cancel in W/Z cross section ratio)

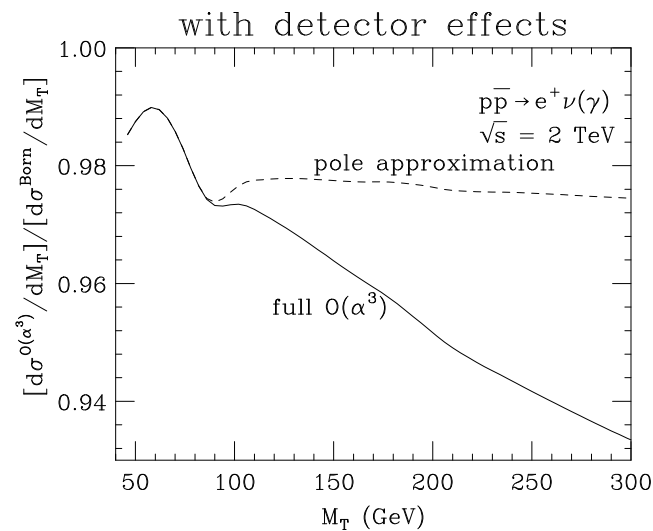
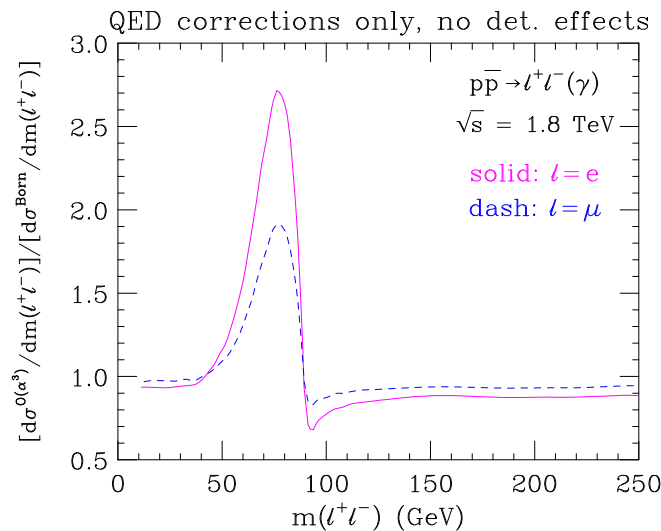
- ☞ for consistent treatment need PDF's which include QED corrections. These are available in **MRSTQED04** set

Anatomy of the EWK $\mathcal{O}(\alpha)$ Corrections

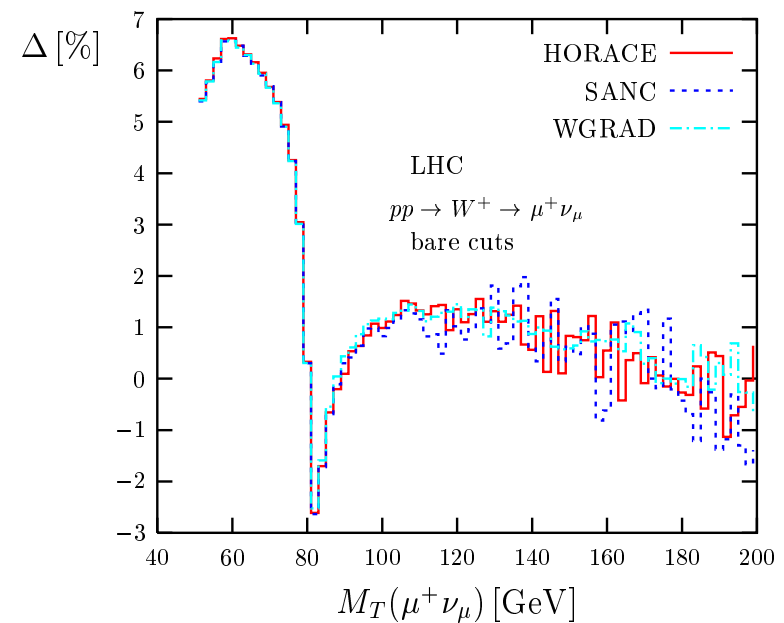
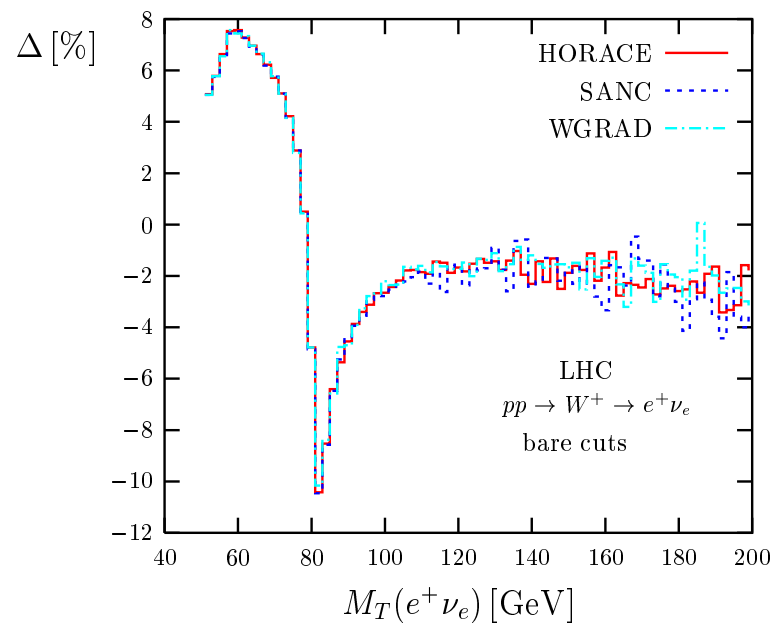
- 1-loop EWK corrections shift W and Z masses by $\mathcal{O}(100 \text{ MeV})$
 - most of the effect comes from final state photon radiation
 - proportional to

$$\frac{\alpha}{\pi} \log \left(\frac{\hat{s}}{m_\ell^2} \right)$$

→ these terms together with the Sudakov logs significantly influence the $\ell^+ \ell^-$ inv. mass distribution and $\ell \nu$ transverse mass distribution (pole approximation: no Sudakov logs are present)



- the existing calculations of the full $\mathcal{O}(\alpha)$ corrections agree in most cases within the statistical uncertainty of the MC integration (**TeV4LHC report [arXiv:0705.3251]** and **Les Houches 2005 proceedings [arXiv:0803.0678]**)
- sample results from a tuned comparison:

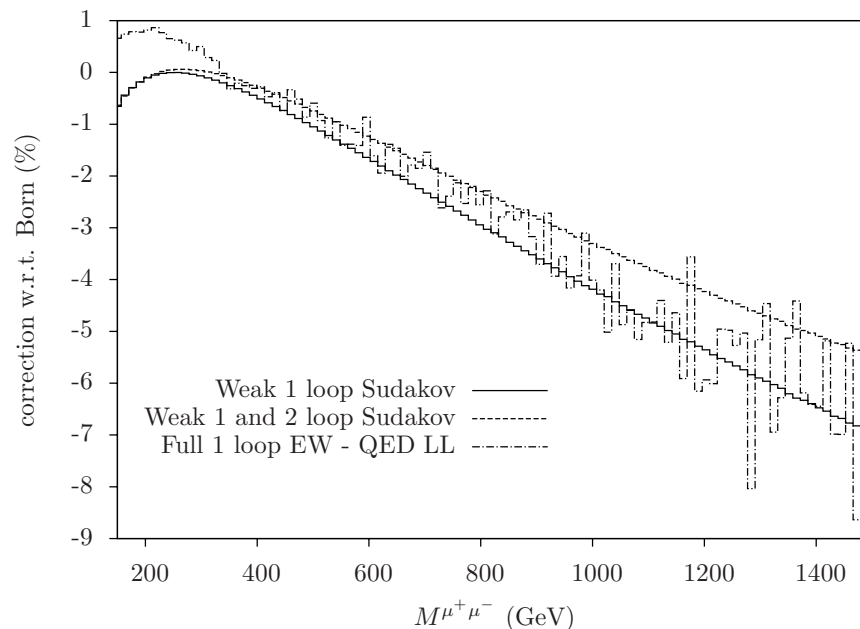


Multi-photon Radiation Effects

- if final state photon radiation shifts W mass by $\mathcal{O}(100)$ MeV:
 - ➡ need to worry about multiple (final) state photon radiation in W and Z production
 - ➡ two photon radiation is known to significantly change the shape of the $m(\ell\ell)$ and M_T distributions (UB, T. Stelzer, 1999)
 - ➡ multi-photon radiation in W decay has been incorporated in WIN-HAC
 - ➡ multi-photon radiation in W and Z decays are also integrated in HORACE
 - ➡ multi-photon radiation shifts M_W, M_Z by $\mathcal{O}(10)$ MeV

Electroweak Sudakov Logs

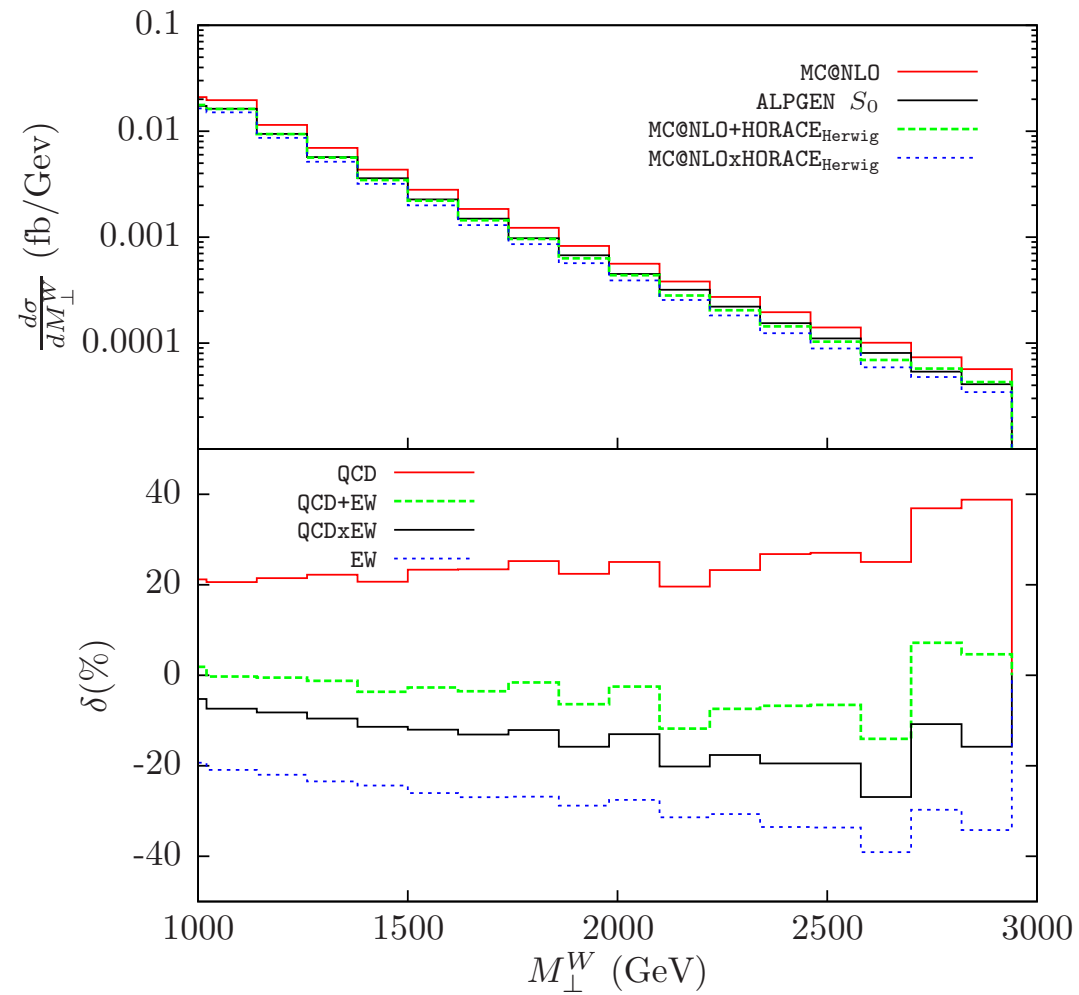
- for $\hat{s} \gg M_{W/Z}^2$, the weak corrections become **large and negative**
- for LHC energies it is necessary to resum Sudakov logs
- Logarithmic corrections are known to NNNLL accuracy (**Kühn et al.**)
- Sudakov logarithms have been implemented in **ZGRAD** and **HORACE** (**arXiv:0803.0678**)



Combining QCD and EW corrections

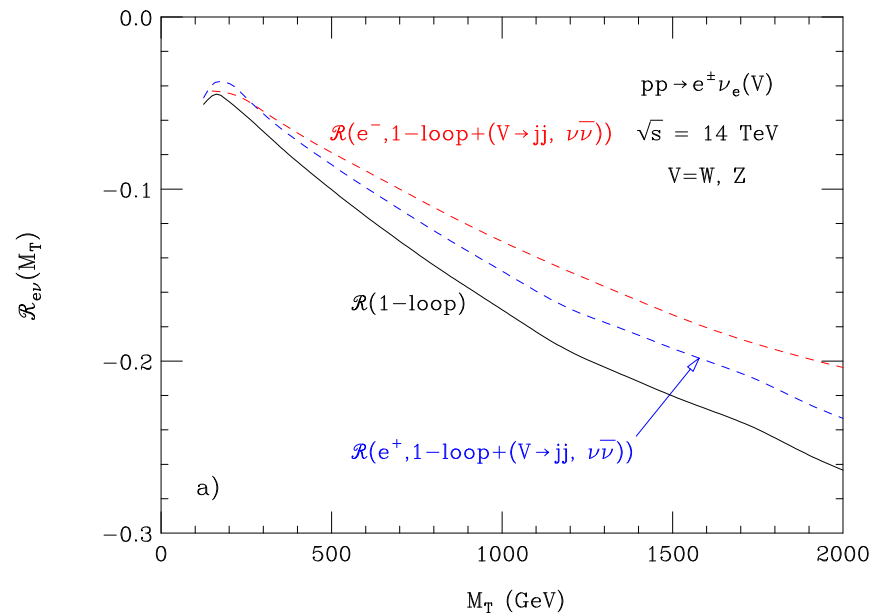
- In order to achieve $\delta M_W \approx 10$ MeV or better, a calculation which combines QCD and EW corrections is needed
 - ☞ EW corrections shift the W mass extracted from data
 - ☞ QCD corrections smear the Jacobian peak of the M_T distribution and thus limit the precision which can be achieved
- First step: final state QED bremsstrahlung has been included in **RES-BOS** (Cao, Yuan)
- A combination of QCD and EW corrections is also needed for large $\ell^+ \ell^-$ ($\ell \nu$) invariant masses, where EW corrections can be as large in magnitude as the NLO QCD corrections
 - ➡ this region is important for new physics searches (W' etc.)

HORACE



- QCD and EW corrections tend to cancel
- **However**, EW corrections do **not** include real EW corrections, eg. $WW \rightarrow \ell \nu jj$ which may partially cancel the large, negative EW one-loop corrections (**UB**)
- answer depends on whether one looks at **exclusive** or **inclusive** Drell-Yan production

$\mathcal{R}_{e\nu}$: relative correction to LO cross section



- The **HORACE** team has interfaced HORACE with MC@NLO
([arXiv:0907.0276](#))

☞ the procedure for doing this is **not unique**

☞ additive approach:

$$\left[\frac{d\sigma}{d\mathcal{O}} \right]_{QCD\&EW} = \left\{ \frac{d\sigma}{d\mathcal{O}} \right\}_{MC@NLO} + \left\{ \left[\frac{d\sigma}{d\mathcal{O}} \right]_{EW} - \left[\frac{d\sigma}{d\mathcal{O}} \right]_{LO} \right\}_{HERWIG\ PS}$$

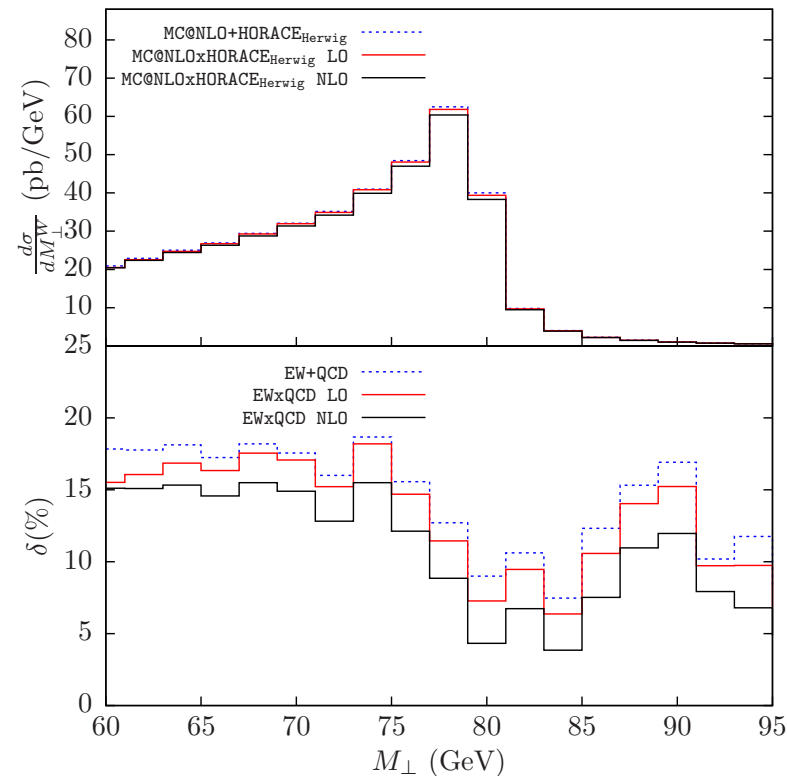
☞ factorized approach:

$$\begin{aligned} \left[\frac{d\sigma}{d\mathcal{O}} \right]_{QCD\&EW} &= \left(1 + \frac{[d\sigma/d\mathcal{O}]_{MC@NLO} - [d\sigma/d\mathcal{O}]_{HERWIG\ PS}}{[d\sigma/d\mathcal{O}]_{LO/NLO}} \right) \\ &\quad \times \left\{ \frac{d\sigma}{d\mathcal{O}_{EW}} \right\}_{HERWIG\ PS} \end{aligned}$$

⇒ defined either in terms of LO or NLO cross section

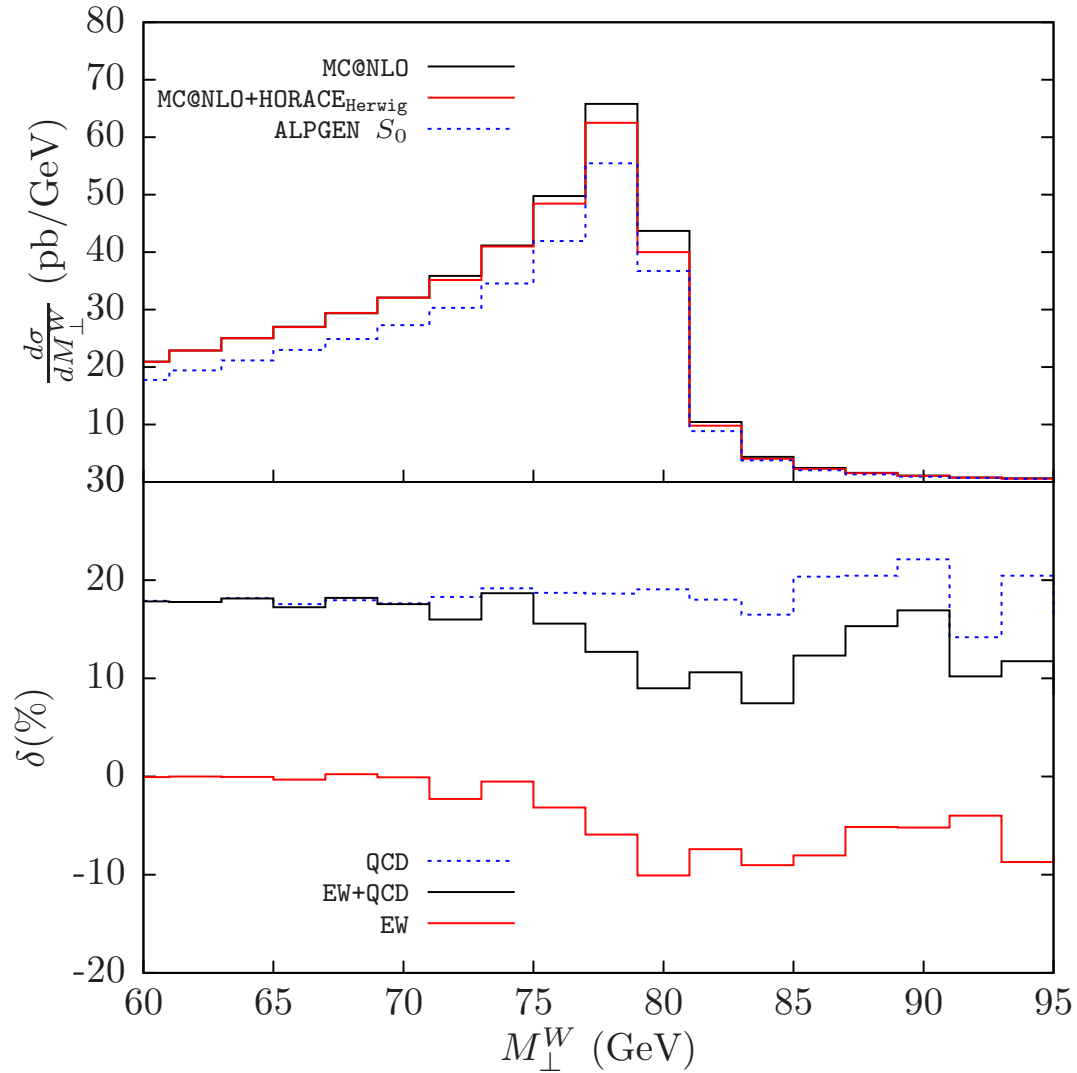
⇒ differ at $\mathcal{O}(\alpha_s^2)$ by non-leading contributions

- the residual uncertainties resulting from the ambiguity between the additive and factorized approach are of $\mathcal{O}(\alpha\alpha_s)$
- they are numerically significant (correspond to shift in M_W of $\mathcal{O}(20 \text{ MeV})$ (**Vicini**))



→ need full $\mathcal{O}(\alpha\alpha_s)$ corrections to quantify

combined QCD and EW radiative corrections in the W peak region



4 – Conclusions

- M_W , together with m_{top} , make it possible to constrain the Higgs boson mass
- need $\delta M_W = \mathcal{O}(10 \text{ MeV})$ to match anticipated precision for m_{top}
- sensitive to new physics via loop corrections
- measuring M_W at the LHC is non-trivial and may require special runs (deuterium, helium) and/or special detector configurations (reverse magnetic field)
- EW radiative corrections affect the M_T line shape and thus the W mass extracted from data
- need better understanding how to combine calculations of QCD and EW corrections into one unified generator

This talk was prepared in a 100% Microsoft free environment